Polarized Gun R&D

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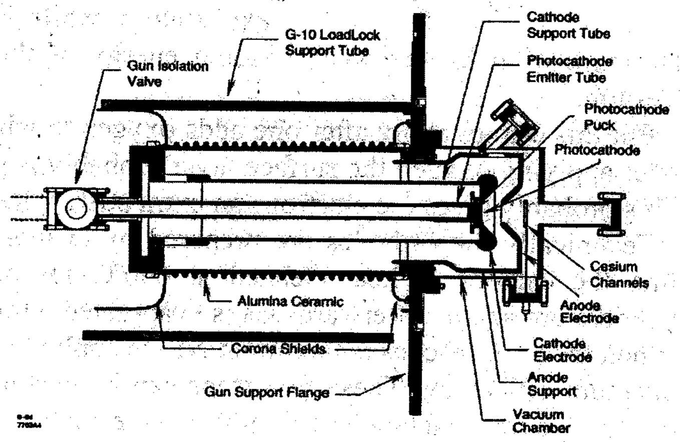
For various reasons it is a stringent requirement that the electron source for the ILC be a polarized one. Therefore it is logical to start development towards a polarized RF gun at A0. Since the conventional polarized electron sources are based on a photocathode the principle can be transferred to the RF gun.

The SLC Polarized Gun

The polarized injector for the Stanford Linear Collider relied on a DC gun with voltages around 120 kV[1]. The surface field at the cathode reached 1.8 MV/m. The cathode was a negative electron affinity (NEA) GaAs cathode. The electrons were produced by a YAG-Ti laser system shining onto the cathode. The bunch length at the cathode was approximately 2 ns and subsequently compressed to a few tens of picoseconds to suit the S-Band linac.

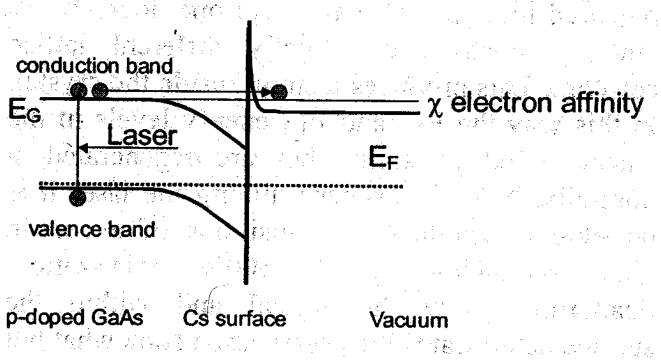


The normalized gun emittance at the space charge limit was calculated to be 35 mm mrad. The cathode diameter was 20 mm and the distance to the anode 3 cm.

The vacuum pressure was very good with a total pressure around 10^{-11} Torr, dominated by hydrogen. Other species like CO and N_2 were at partial pressures of $2\cdot10^{-12}$ Torr, H_2O was at $2\cdot10^{-13}$ Torr. The importance of these values will be explained later.

Negative Electron Affinity

In the figure on the left the negative electron affinity is explained in the energy band diagram. Bulk GaAs has a work function of 5.5 eV. The energy gap between the valence band to the conduction band is 1.4 eV. The material is heavily p-doped, therefore the Fermi energy level is pinned just above the valence band limit. A high density of surface states bends the energy bands



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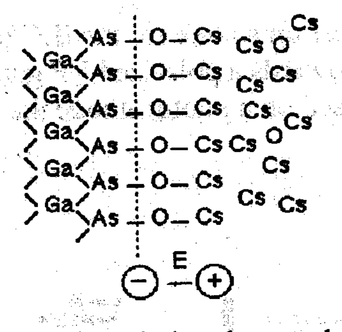
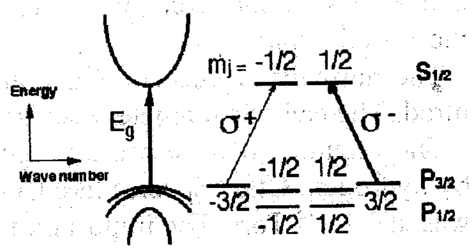
downwards. The existence of the surface states is one result of the Cs treatment of the surface. This bending amounts to about 0.9 eV. The remaining 3.3 eV are accounted for in the Cs surface layer. Then the vacuum energy level is below the lowest energy of the conduction band, and electrons that are promoted into the conduction band can tunnel through a thin surface barrier into the vacuum.



I was not entirely satisfied with the explanations I found on what actually causes this huge drop in work function. I found a paper on this[2], reporting that it has been explained by the polarization of the Cs or CsO, respectively. The author himself does not believe this explanation, while I in turn have my problems with his. He explains it by the weak binding energy of the electrons in the outer shell of the Cesium.

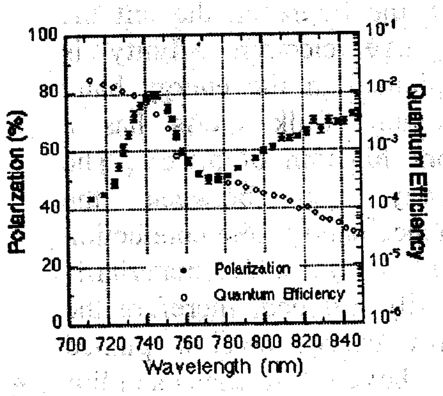
But this cannot apply after one adds oxygen in which case the Cs gets ionized. At least after applying oxygen the surface layer probably is polarized as shown in the left picture. This probably gives the electrons an extra push, which boosts them out into the vacuum.

Technically the cathodes are prepared by evaporating Cs onto the surface. Therefore first the cathode is heat cleaned at 600°C for one hour and cooled down to room temperature again. Afterwards Cs is evaporated while monitoring the quantum efficiency. When the Q.E. reaches a maximum NF_3 is applied via needle valve to further increase the quantum efficiency. These two steps can be performed alternating a few times, the so-called "yo-yo" methode. Slightly overcesiating improves the lifetime of the cathode.



Polarization

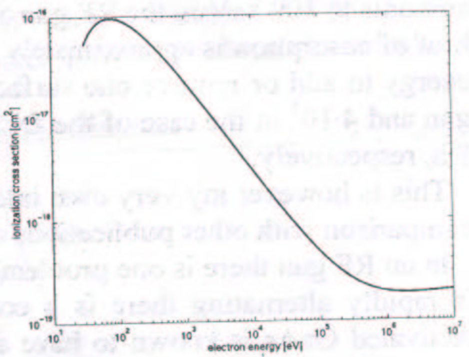
The polarization that can be achieved from bulk GaAs is limited to 50%, meaning that one orientation exceeds the other by 50%. This value can be enhanced by a lot when the cathode is prepared in a special way. Here one does not use bulk material but the GaAs is grown onto a substrate of slightly different lattice constant. This produces a strain inside the crystal. In this way the $P_{3/2}$ and $P_{1/2}$ energy levels in the valence band get split. They are degenerated in normally. Now by properly tuning the laser it is possible to excite only transitions of a certain kind, producing up to 100% polarization. Scattering inside the crystal and within the surface deteriorates the polarization somewhat but 80-90% in vacuum are feasible. The second plot on the right shows the polarization and quantum efficiency versus laser wavelength, illustrating the effect. At the same time this plot allows to infer the electron affinity. It is about –0.02 eV between the "sweet spot" and a drastic drop in electron yield. To be exact this is not the



true c as depicted above, since that value compares asymptotic energy levels far away from the surface. It is actually the energy where the surface barrier significantly increases.

Problems

The "magic" of the NEA cathode happens in about one monolayer of CsO. It can be easily imagined that it does not take very much to destroy the layer and hence the effect. And indeed it has been found that NEA cathodes are very sensitive to their environment. In DC guns two main reasons for surface damage have been identified: Chemical reactions with the residual gas and ion bombardment. Improving the vacuum of the gun can best cure both. In the case of the SLC gun a vacuum pressure of 10^{-11} Torr was achieved, dominated by H_2. Hydrogen does no harm to the cathode chemically. The greatest danger stems from water, oxygen, and anything containing carbon. Therefore the partial pressures of these species have to be 10-100 times lower.

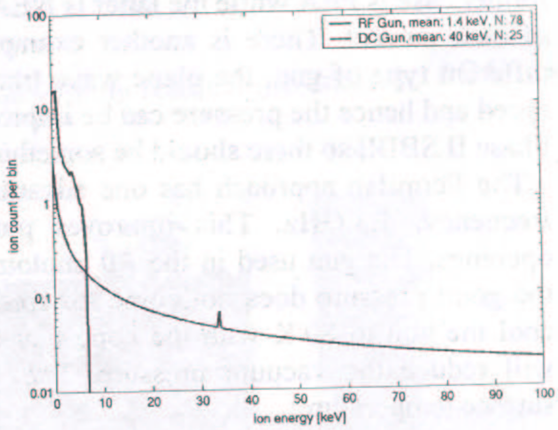


Once these pressures are reached, the main damage comes from ion bombardment. Since electrons that are accelerated in the gun generate the ions, cathode lifetimes are often quoted in terms of charge accelerated (Unfortunately this can be dark current as well). To get a handle on how much damage can be done consider the following. The energy bands are bent by 0.9 eV. This is caused by electron donors on the surface of the GaAs. The number of donors is calculated by[3]

$$\Delta N_d = \sqrt{\varepsilon_r \varepsilon_0 N_a \Delta\varphi / e_0}$$

which amounts to $5\cdot10^{12}$cm^{-2} for ε_r=12 and N_a=$5\cdot10^{18}$cm^{-3}. To change this by 0.02 eV, only $6\cdot10^{10}$ cm^{-2} donors need to get lost. Compare this to about $6\cdot10^{14}$ cm^{-2} atoms on the surface. Now assume that the ions cause donors to get lost or acceptors being created.

The ions are generated by high-energy electrons in the residual gas. Since the gas consists mainly of H_2 molecules, the ions will mostly be H_2^+. In an RF gun H_2 ions are the most dangerous because they achieve the highest energies (except for H^+). The ionization cross section quickly drops with the energy of the electrons. Therefore most of the ions originate from the vicinity of the cathode. A simple program to track the ions in one dimension yields the figure on the right. Two cases have been considered here, and 1.3 GHz, 1.6-cell RF gun at 35 MV/m, and a DC gun with gap length 2 cm and 200 kV acceleration voltage (the deviation from the SLAC gun is accidental). Because of the larger active



volume of the RF gun there are more ions generated than in the case of the DC gun. But the ions quickly get out of sync with the RF field and therefore reach only 7 keV maximum (14 in the case of H^+). Therefore the mean energy deposition in the RF gun is lower than in the DC gun. The penetration depth is below 1Å in all cases, meaning that the ions are stopped in the surface layer. The energy deposition per beam (macro-)pulse amounts to 109 keV in the RF gun and 900 keV (now 3cm & 120 kV) in the DC gun. The heat of adsorption is approximately 2.6 eV for Cs on GaAs. Assuming that this about the energy to add or remove one surface state, there will be $4\cdot10^4$ states changed in the RF gun and $4\cdot10^5$ in the case of the DC gun. This can be converted into a lifetime of 83 h or 8 h, respectively.

This is however my very own interpretation. The relation to reality has to be found by comparison with other publications or with experiment.

In an RF gun there is one problem that does not appear in a DC gun. Since the RF field is rapidly alternating there is a constellation in which electrons can hit the cathode. Activated GaAs is known to have a very large secondary electron yield in the order of 100. And in fact there have been reports of greatly enhanced dark current production from an activated GaAs[4]; the factor was indeed about 100.

What to do

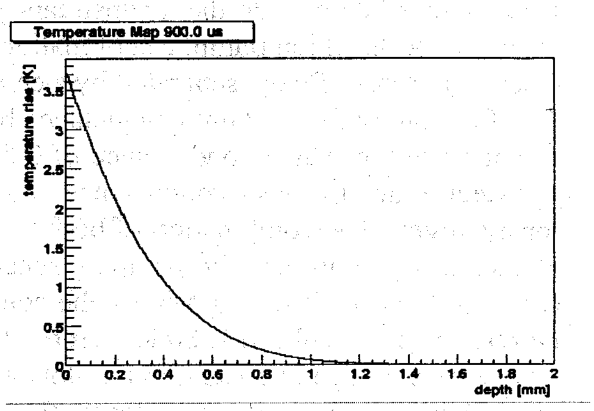
Before caring for other things first the vacuum inside the RF gun has to be improved to reach the required 10^{-11} range that is achieved in DC guns. In terms of cathode poisoning, gases like H_2O, O_2, CO, and CO_2 are especially harmful. There have been earlier attempts to use a GaAs cathode in RF guns. In Novosibirsk and at CERN[5] S-band guns were tested without special modifications to the gun itself. The CERN results showed a long lifetime probably due to the use of green laser light instead of infrared. In this case there will still be photoemission when the cathode has a positive electron affinity. The Novosibirsk results are especially confusing because the quoted lifetimes differ by orders of magnitude. In one paper 30 minutes are reported in another its only seconds (after reducing the rep-rate). In both cases they just say the cathode is activated. But maybe the former case is PEA while the latter is NEA. In both cases however they see huge amounts of dark current. There is another example at SLAC[6]. Here they actually change to a different type of gun, the plane wave transformer (PWT), in the hope that the pumping speed and hence the pressure can be improved. I do not know of any results yet, but it is a Phase II SBIR, so there should be something in the near future.

The Fermilab approach has one advantage right away, because it operates at L-band frequency, 1.3 GHz. This improves pumping automatically because of the bigger openings. The gun used in the A0 photoinjector however still only reaches 10^{-9} Torr, so the good pressure does not come for free. To improve the pressure it has been tried to cool the gun to 80 K with the hope that this reduces outgasing from the surface which will reduce the vacuum pressure. The gas desorption exponentially depends on the surface temperature:

$$\frac{dN}{dt} \propto N\exp\left(-\frac{E}{RT}\right)$$

For an adsorption energy E of about 10 kJ/mol (CO on copper) this would mean a factor of 10^5! Additionally there are three sublimation pumps and three ion pumps attached to provide enough pumping. The gun was carefully cleaned and assembled, and it was baked at 130°C for 24 h. The limit here was a gate valve between the gun and the RGA system, which was Viton sealed. Because of one necessary repair the two sections on either end of the gate valve were baked separately. This may have some impact on the results and will be considered again later.

The tests have been performed with a prototype gun called Gun A. It is a 1.6-cell L-band gun at 1.3 GHz. At a peak cathode field of 35 MV/m it dissipates 2.2 MW. At 80 K the surface resistance is lower, and hence the dissipated power is reduced by a factor of 2.8. Therefore the 35 MV/m are reached with 780 kW, 3.5 kW average. This calls for 10 kW refrigerator power. The heat flux at the cooling pipes is about 2.5 W/cm^2. In earlier discussions with AES we used to compare that with the nucleate boiling limit of 15 W/cm^2. This does not apply however since were not using pool boiling but force the nitrogen through the cooling pipes. In this case the limits are even more relaxed.



To make sure that the temperature does not rise too much during the RF pulse I made a simple simulation to calculate the rise of the surface temperature, assuming the 1-dimensional case of a plane wave hitting a plane surface. In this case the surface

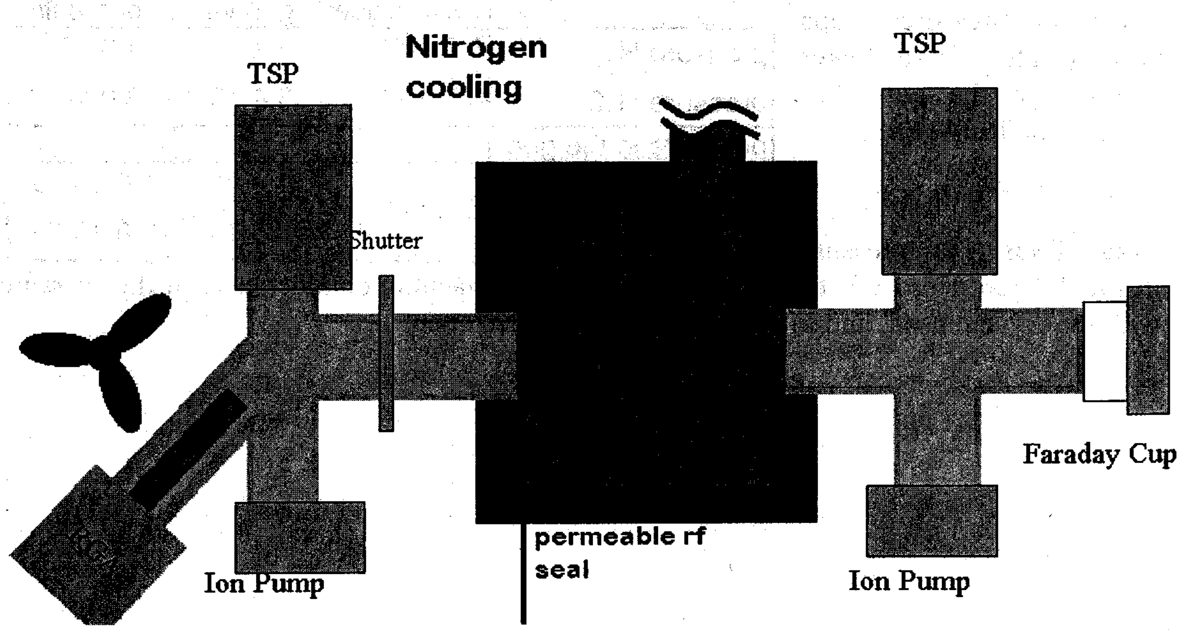
$$T = I\sqrt{\frac{4t}{\pi\rho c\lambda}}$$

temperature rises according to
with T the temperature, t the time, I the intensity, ρ the density, c the heat capacity, and λ the heat conductivity. After 900 μs this is about 3.5 K, hence acceptable.

The tests are divided into three phases: Vacuum tests, Q.E. measurements, gun design. The first phase has been completed.

Phase I: Vacuum Tests

In this phase the basic idea is tested. By performing residual gas analysis (RGA) under



different operating conditions the state of the vacuum is examined. In the figure below the vacuum setup is outlined. In the center there is the nitrogen cooled gun. The cathode has been removed and the remaining hole kept open. Through this hole the vacuum is measured. A 2 ½ inch pipe is connected which ends in a 6-way cross, whose ports house a ion pump, a titan sublimation pump, a pump-out port, and the residual gas analyzer (RGA). A gate valve between the pipe and the 6-way cross allows separating the vacua. A fan is used to cool the vacuum chamber around the RGA head. The filament of the RGA is very close to the pipe walls and causes them to warm up which in turn shows in the data (see below). On the downstream port of the gun a four-way cross is connected, which supports an ion pump, a sublimation pump, and a Faraday cup. The Faraday cup is essentially a steel flange separated by a ceramic ring.

Unfortunately the vacuum conductance between the gun and the RGA is very low. The cathode aperture has a conductance of $2.86*(T/M)^{1/2}D^2 = 15$ l/s for water and 45 l/s for hydrogen. The pipe has a conductance of $3.81*(T/M)^{1/2}D^3/L = 55$ l/s for water and 165 l/s for hydrogen. The combination of both has a conductance $C = (1/C_1+1/C_2)^{-1}=12$ l/s resp. 36 l/s. At the same time the pumping speed of the sublimation pump is 110 l/s for water and 330 l/s for hydrogen, given by the conductance of the pipe towards the pump. These numbers were calculated at 80 K, at room temperature they approximately double.

On the next page two RGA trend plots at room temperature are compared. The top one was taken with the gate valve closed, the other one with the gate valve open, just before and during cooling down.

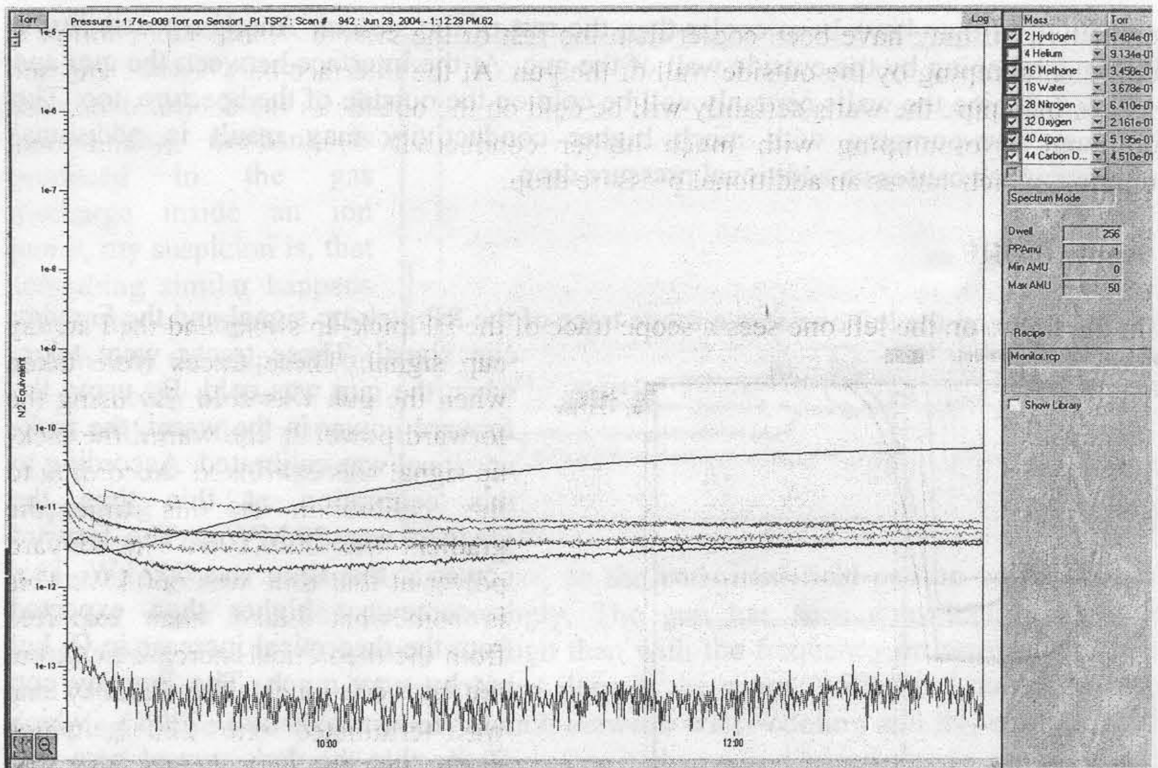
In the trend plot on top one sees the development of the partial pressures from switching on the RGA until it almost reaches equilibrium. The pressure first drops rapidly after some dirt that settles in the vicinity of the ion source is evaporated. After reaching a minimum the pressure rises again because the surrounding vacuum pipe warms up. The fan reduces this but does not eliminate this. C. Sinclair suggests to let the filament penetrate deeper into the chamber so that there is less surrounding surface. But caution: The pipe around the mass filter has to stay, it is part of a resonant circuit.

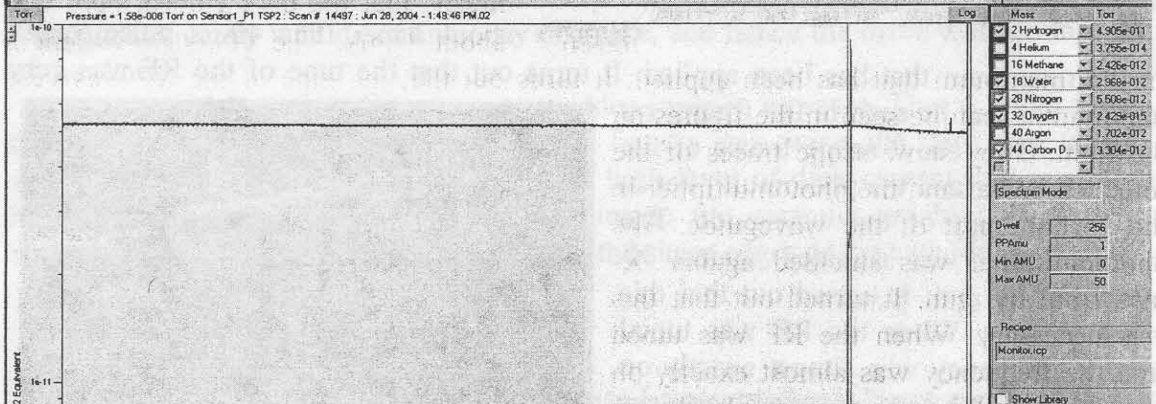
From the pressure readings at equilibrium one can infer the pressure inside the gun. The results are summarized in the table on the right. According to that table the basic requirements for hydrogen are already met in the warm, the water pressure is already good; it may even improve with a bake-out at higher temperature. The pressures were calculated by assuming there was a constant gas load Q in the apparatus around the RGA. By adding the gun to the system the pressures drops because there is a lower pressure in the gun than close to the RGA. From

$$p_g = p_2 - \frac{S}{C}(p_1 - p_2)$$

one finds the pressure inside the gun. Here S is the pumping speed, C the vacuum conductance, p_1 the pressure with the valve closed, and p_2 the pressure with valve open.

	valve closed	gun warm	gun cold
pressure H_2	$5.5\ 10^{-11}$	$5.1\ 10^{-11}$	$4.9\ 10^{-11}$
pressure H_2O	$3.7\ 10^{-12}$	$3.4\ 10^{-12}$	$3.0\ 10^{-12}$
pressure in the gun			
H_2		$1.4\ 10^{-11}$	$-8\ 10^{-12}$?
H_2O		$5.6\ 10^{-13}$	$-6\ 10^{-12}$?

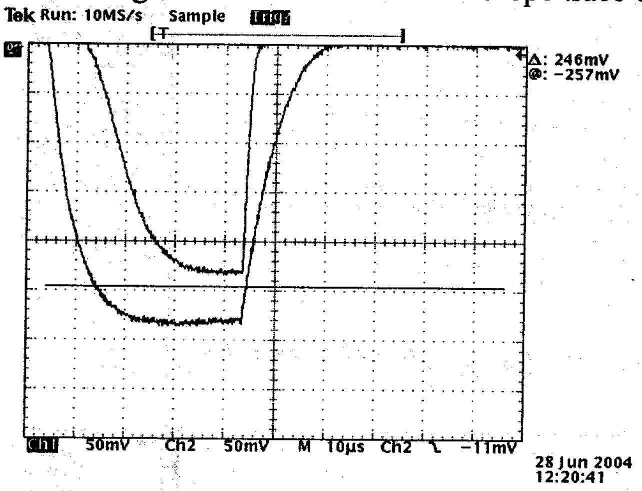


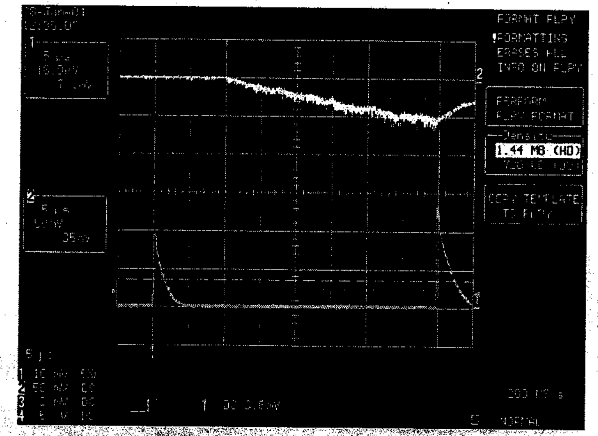


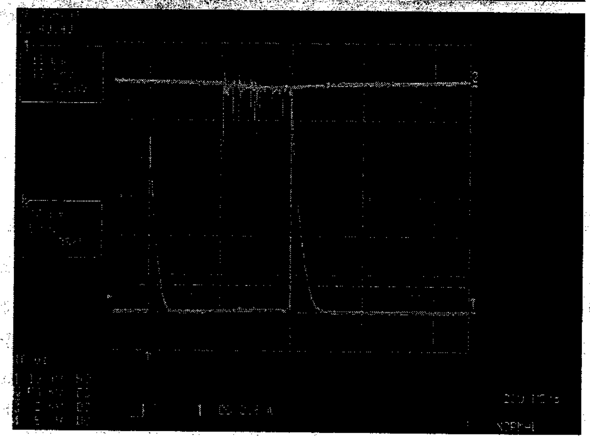
Apparently there is a problem calculating the pressure in the cold. In this case the above formula delivers negative pressures, which is obviously wrong. There are a few possible explanations for that. First there may be additional gas load from the gate valve. This would result in an overestimate of the pressure drop due to opening the valve. The valve was closed during the bake, meaning that the blade was exposed, but due to poor heat conductivity it may have been cooler than the rest of the system. Another possibility is additional pumping by the outside wall of the gun. At the interface between the gun and the 2-½ inch pipe the walls certainly will be cold on the outside of the aperture, too. The additional cryo-pumping with much higher conductivity may result in additional pumping, which causes an additional pressure drop.

Apply the RF

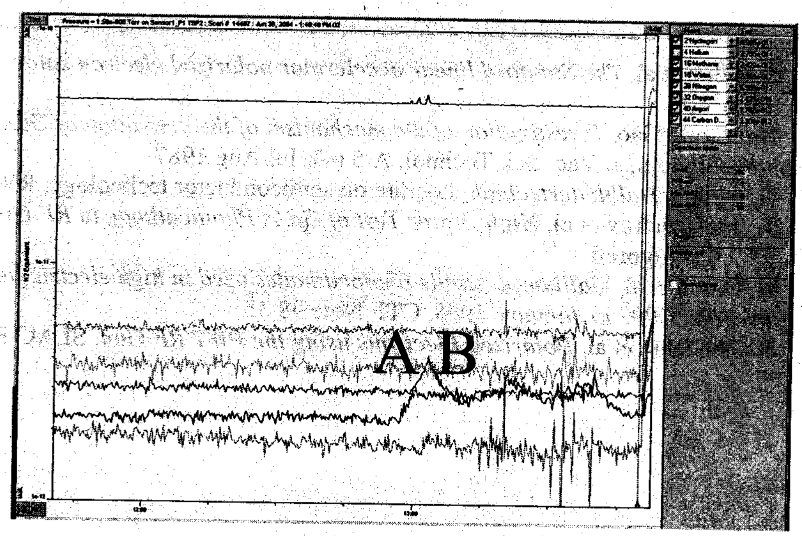
In the figure on the left one sees a scope trace of the RF pick-up signal and the Faraday cup signal. These traces were taken when the gun was cold. By using the forward power in the warm, the pick-up signal was calibrated. According to this calibration at this time the gradient was 29 MV/m. The forward power at that time was 660 kW. This is somewhat higher than expected from the theoretical increase in Q, but not by very much. The Faraday cup was terminated into 220 Ω, which means that the dark current here was about 1 mA. The 40 µs pulse length are the maximum that has been applied. It turns out that the tune of the RF was very important as can be seen in the figures on the right. They show scope traces of the reflected power and the photomultiplier in the vacuum part of the waveguide. The photomultiplier was shielded against X-rays from the gun. It turned out that this was necessary. When the RF was tuned first the frequency was almost exactly on resonance. In this case one can clearly see a continuous build-up of light inside the waveguide. After retuning the drive frequency above resonance, the light production is significantly reduced as can be seen in the second plot. Even though there is more RF going into the cavity the production of light is much smaller and less coherent.







When looking at the trend plot of the RGA during that time one sees some activity of the methane. In the first case with large amount of light, the partial pressure of methane rises (A), in the second case with little light, the methane-pressure drops, even though the power is increased (B). Since it is known that methane is produced in the gas discharge inside an ion pump, my suspicion is, that something similar happens inside the waveguide. The reason why this depends on the frequency of the RF has to do with the field pattern inside the waveguide. Depending on the frequency the reflected power changes its amplitude and phase, so the combined field pattern of forward and reflected wave will change accordingly. The gun has seen considerably more RF conditioning with the frequency too high than with the frequency on resonance. This is due to the fact that the conditioning was done in the warm. With this I hoped for better pumping. Since I could not easily switch between water-cooling and lN_2-cooling, in the warm the gun was not cooled at all. Therefore it always had a tendency to expand and the resonant frequency would continuously decrease, and hence the drive was too high most of the time.



At the end of the trend plot one sees a sudden jump in pressure. That is when a leak in the ceramics of the Faraday cup occurs. We fixed a leak twice, the third time (which is shown here) I just gave up afterwards. The high level of dark current that is produced most certainly caused the leaks. A liner inside the ceramics might help with that. Hopefully the dark current is only caused by the sharp edges of the cathode port!

Conclusion

Most of the measurements foreseen for phase I are completed. There are some question marks on the pressure measurements, but I do not see how one could improve these easily (maybe somebody else has a good idea). With the high level of dark current there may be however a way to measure ion currents, the production rate should be large enough. From the ion currents one might be able to conclude on the pressure as well. Or take the ions as the quantity of interest.

I made comments for possible improvements throughout the text. AES will build a cathode system. Unfortunately we did not clearly say who will pay for the gate valve between the gun and the cathode chamber, but the perception is that this should be an all-metal sealed one (those do not come cheap). This removes concerns about outgasing and allows higher bake temperatures. Which brings me to the question of opening the gun for repair of the Faraday cup. It certainly would be a good idea to make baking the gun easier. The simplest probably is to route the cooling pipes somewhat lower and modify the box such that one can take off the walls without coming into conflict with the pipes.

[1] R. Alley et al, *The Stanford linear accelerator polarized electron source*, Nuclear Instr. Meth. A 365 (1995) 1-27

[2] Huai-rong Gao, *Investigation of the mechanism of the activation of GaAs negative electron affinity photocathodes*, J. Vac. Sci. Technol. A 5 (4), Jul/Aug 1987

[3] H. Heime, *Halbleitertechnik*, Lecture on semiconductor technology, RWTH Aachen

[4] A. Aleksandrov et al, *High Power Test of GaAs Photocathode in RF Gun*, EPAC 98, Stockholm and LC97, Zvenigorod

[5] H. Braun et al, *Gallium Arsenide photocathodes used in high electric fields, Results of experiment from November 1997 to January 1998*, CTF Note 98-13

[6] J. Clendenin et al, *Polarized Electrons using the PWT RF Gun*, SLAC-PUB-9550